



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-CONF-562583

Magnetic Guiding for Electron Fast Ignition

D. J. Strozzi, M. Tabak, D. J. Larson, H. D. Shay, L. Divol, A. J. Kemp, C. Bellei, M. M. Marinak, M. H. Key

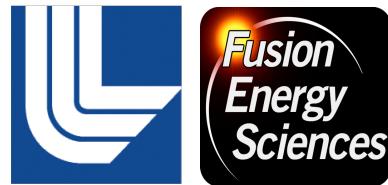
June 27, 2012

Anomalous Absorption Conference
Key West, FL, United States
June 24, 2012 through June 29, 2012

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

Magnetic Guiding for Electron Fast Ignition



D. J. Strozzi

Lawrence Livermore National Laboratory

42nd Anomalous Absorption Conference
Key West, Florida, USA

June 28, 2012

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Supported by OFES HEDLP project FI-HEDS, and LDRD project 11-SI-002.
LLNL-CONF-562583

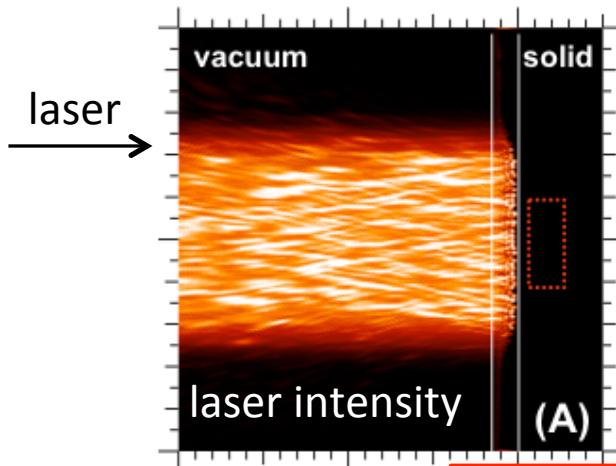
Magnetic pipes can guide electrons to fast-ignition hot spot

- Fast electron source:
 - too energetic to stop in DT hot spot
 - large angular divergence
- Imposed axial magnetic field ~ 50 MG overcomes divergence
 - Magnetic mirroring: increasing field reflects electrons back to source
 - Magnetic pipe: hollow field inside beam radius – prevents mirroring
- Azimuthal pipe of right sign works better than axial pipe:
 - Agrees with expectation from orbits
- Sign of axial pipe matters!
 - Not based on orbits, or resistive Ohm's law $E = \eta J_{\text{return}}$
 - non-resistive terms in Ohm's law gives different field evolution
- Co-authors: M Tabak, D Larson, H Shay, L Divol, A Kemp, C Bellei, M Marinak, M Key

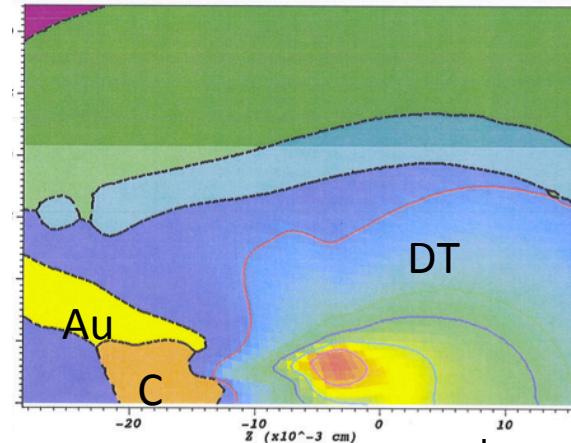


Fast ignition modeling at LLNL

Explicit PIC for short-pulse laser-plasma interaction: A. J. Kemp, L. Divol

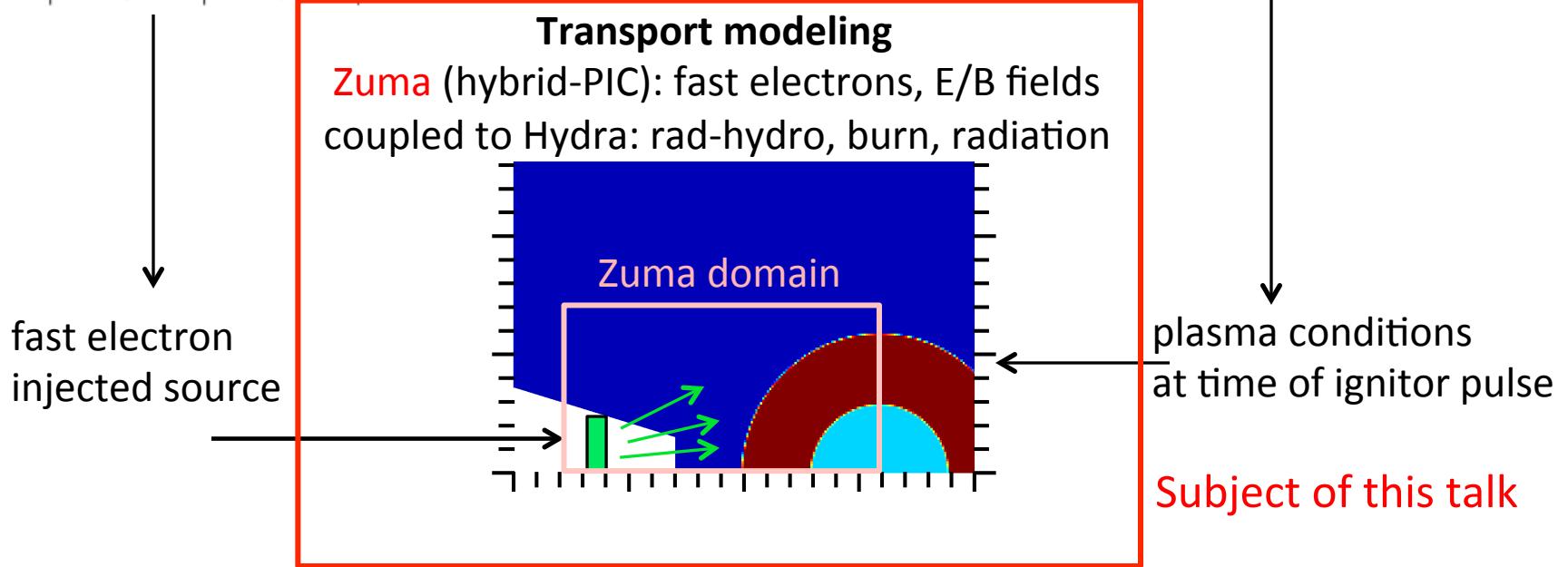


Rad-hydro: fuel assembly in hohlraum, around cone: H. D. Shay, M. Tabak, D. Ho



Transport modeling

Zuma (hybrid-PIC): fast electrons, E/B fields coupled to Hydra: rad-hydro, burn, radiation



Zuma: D. J. Larson: Hybrid PIC code for fast electron transport in collisional plasmas

- RZ cylindrical (this talk) or 3D Cartesian geometries
- Reduced dynamics: no light, plasma waves: $\omega \ll \omega_{pe}, \omega_{laser}$ $k \ll k_{laser}, \lambda_{Debye}^{-1}$
- Electric field from Ohm's law = massless momentum eq. for background electrons:

$$m_e \frac{d\vec{v}_{eb}}{dt} = -e\vec{E} + \dots = 0 \quad \rightarrow \quad \vec{E} = \vec{E}_C + \vec{E}_{NC}$$

$$\vec{E}_C = \vec{\eta} \cdot \vec{J}_{\text{return}} - e^{-1} \vec{\beta} \cdot \nabla T_e \quad \vec{E}_{NC} = -\frac{\nabla p_e}{en_{eb}} - \vec{v}_{eb} \times \vec{B}$$

Resistive Ohm's law: $\vec{E}_C = \eta \vec{J}_{\text{return}}$

$\vec{\eta}, \vec{\beta}$ from Lee-More-Desjarlais and Epperlein-Haines

Relativistic fast electron advance: $\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$

- Fast e- energy loss and angular scattering [Solodov, Davies]

- $\vec{J}_{\text{return}} = -\vec{J}_{\text{fast}} + \mu_0^{-1} \nabla \times \vec{B}$ Ampere w/o displacement current

- $\vec{J}_{\text{return}} \cdot \vec{E}_C$ collisional heating

- $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$ Faraday

Full Ohm's law results differ from $E = \eta^* J_{\text{return}}$

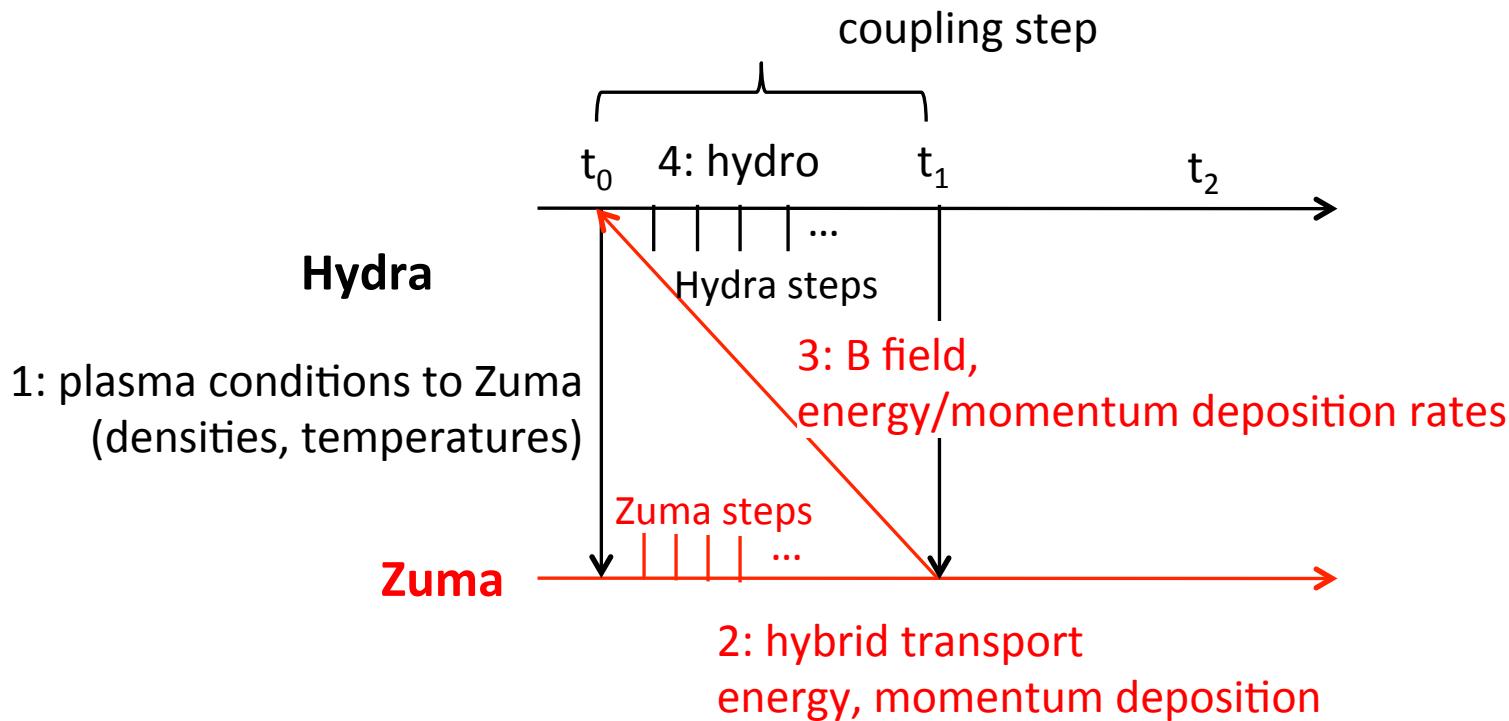
Nicolai et al., APS DPP 2010,
Phys Rev E **84**, 016402 (2011)

Strozzi et al., IFSA 2011 (submitted)

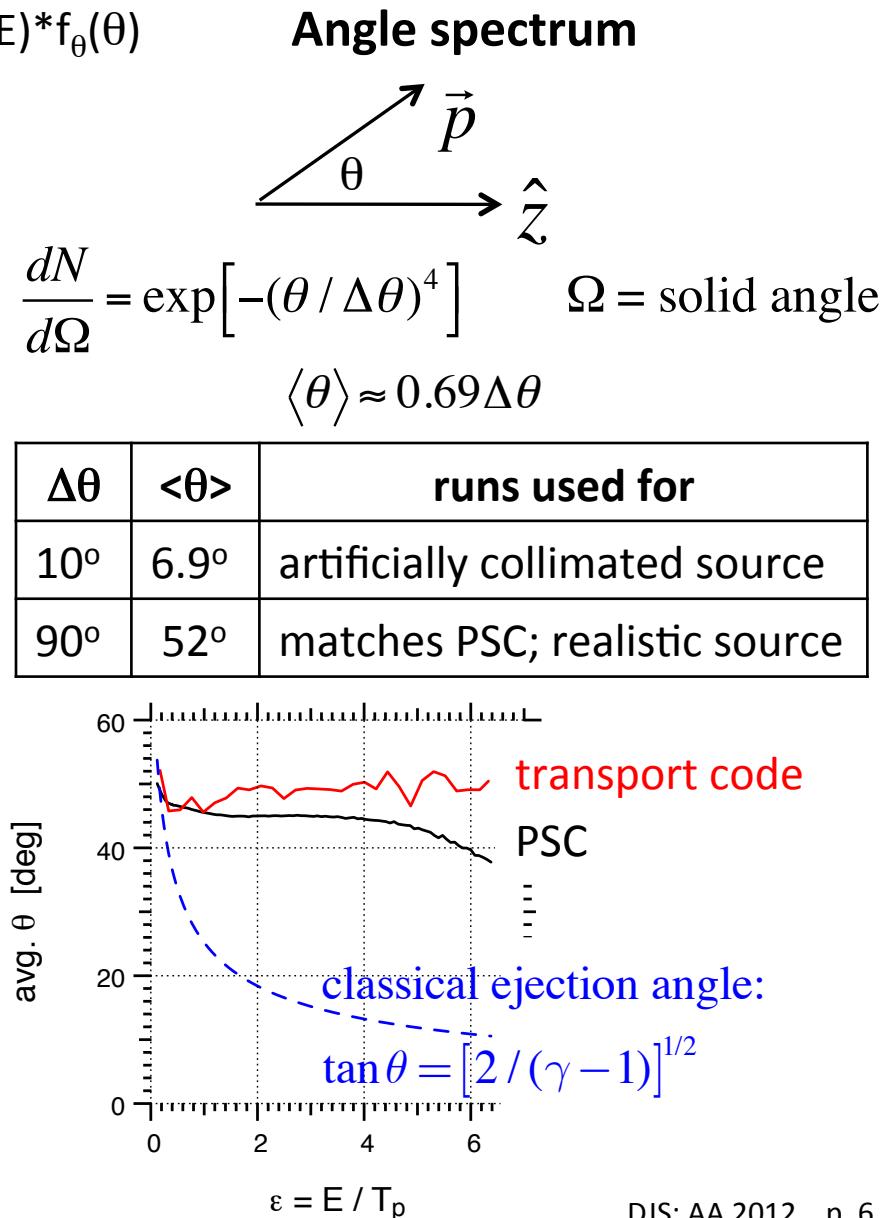
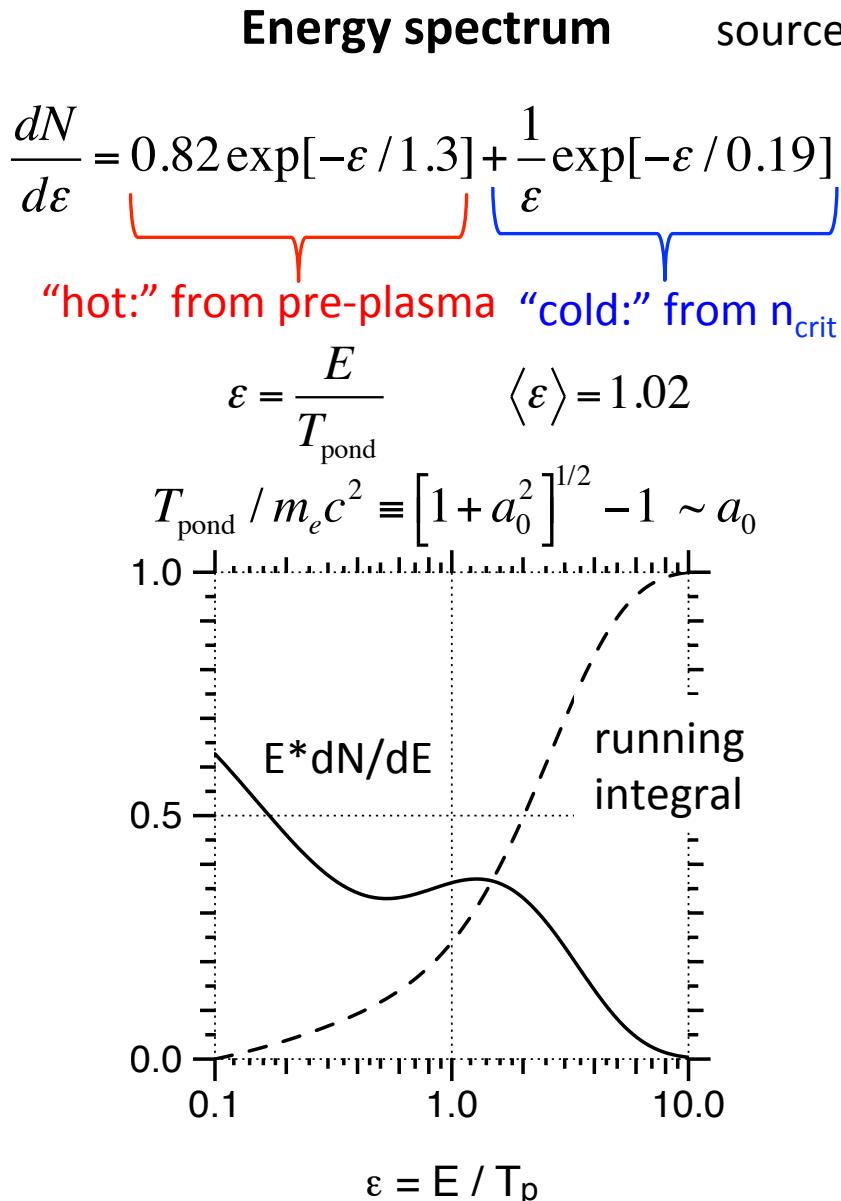
Hybrid PIC code Zuma coupled to rad-hydro code Hydra

(M. M. Marinak, D. J. Larson, L. Divol)

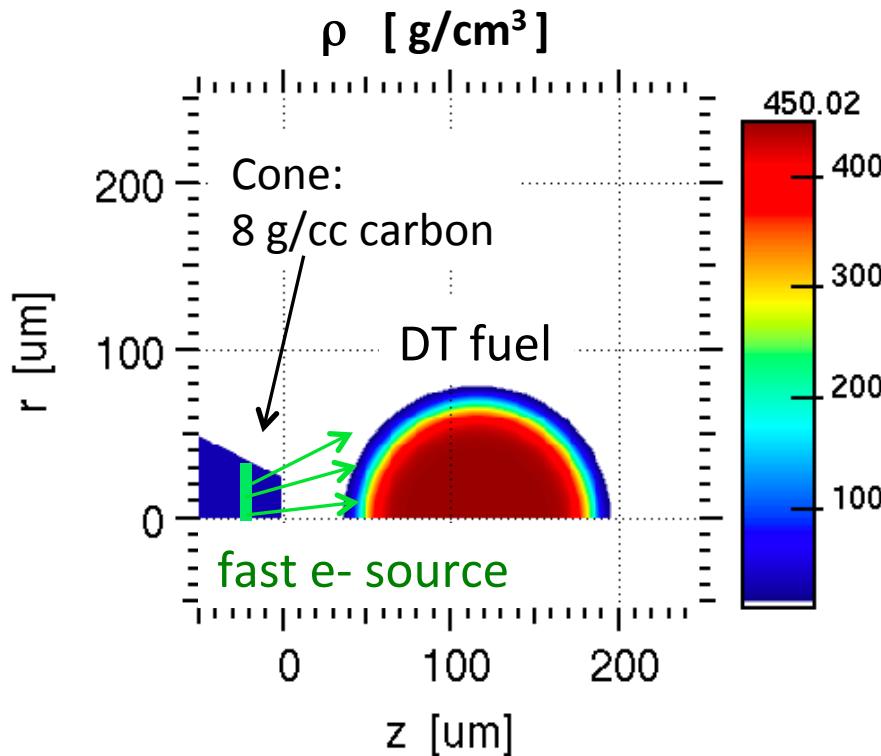
- This talk:
 - both codes in R-Z geometry, fixed Eulerian meshes
 - 20 ps transport (Zuma + Hydra), then 180 ps burn (just Hydra)



Electron spectra from PSC full-PIC sims (A. J. Kemp, L. Divol)



Idealized high-gain target: carbon cone, ideal ignition energy of 8.7 kJ

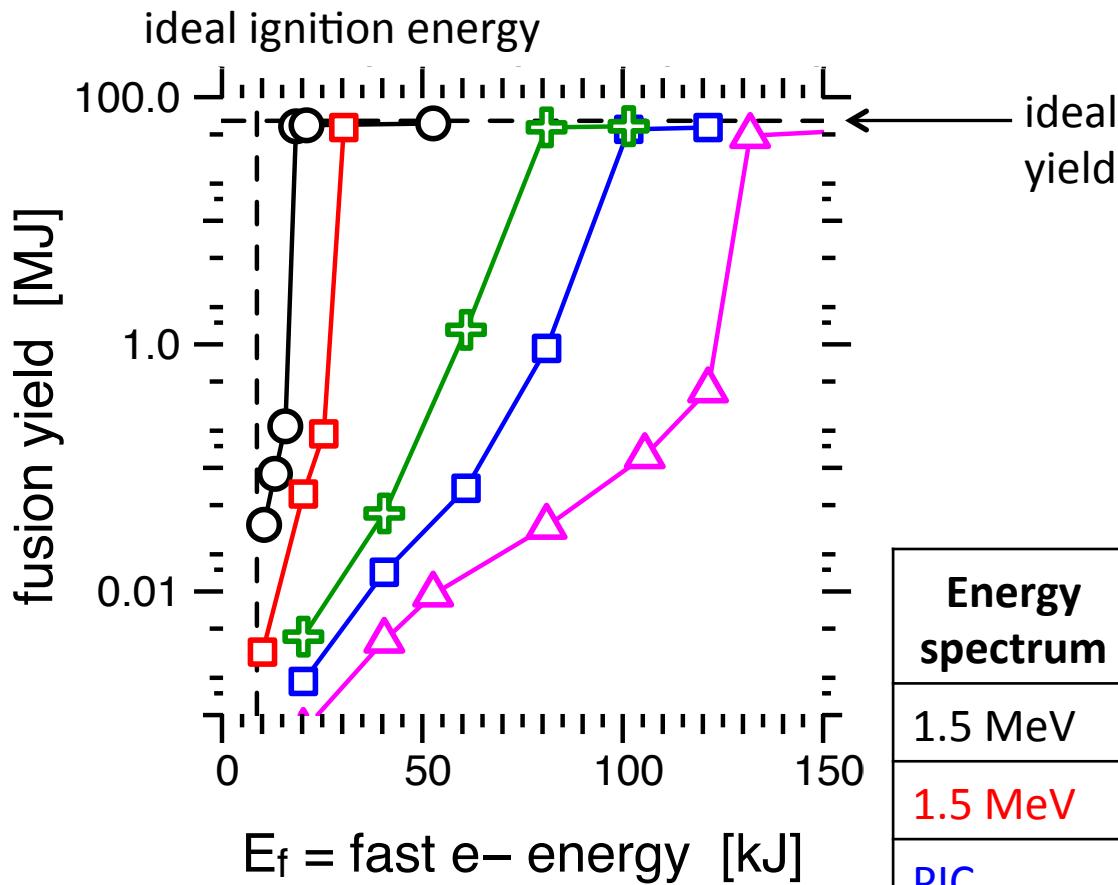


- Ideal burn-up fraction: $\rho R / (\rho R + 6) = 1/3$
- Ideal fusion yield = 64 MJ

Ideal e- ignition energy [Atzeni et al., PoP 2007]:

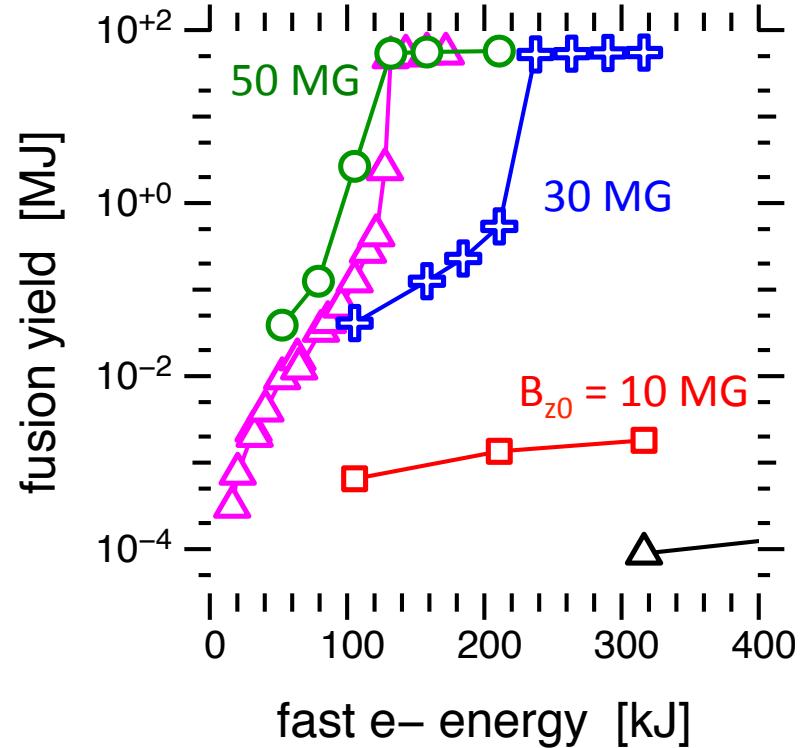
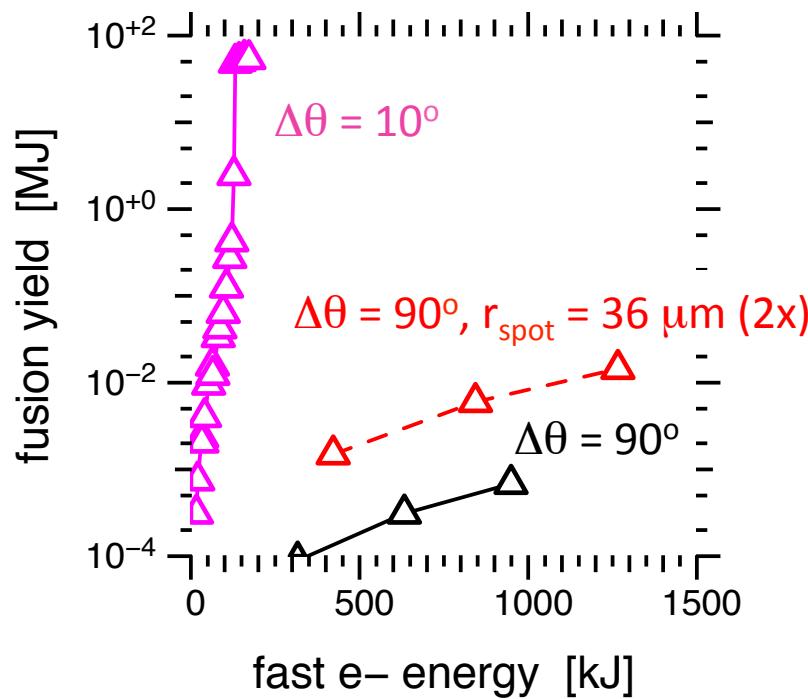
- 2D rad-hydro, no cone, cylindrical beam heat source
- $$E_{ig} = 140 \text{ kJ} / (\rho/100 \text{ g/cc})^{1.85}$$
- $$= 8.7 \text{ kJ}$$
- minimum goal
- 527 nm (2ω) wavelength laser: lowers $T_{\text{pond}} \sim \lambda$

Ignition energy is 15x ideal value with collimated electron source



Energy spectrum	initial $\Delta\theta$	angular scattering	E/B fields
1.5 MeV	0	no	none
1.5 MeV	10°	yes	none
PIC	10°	yes	none
PIC	10°	yes	$E = \eta J_{\text{return}}$
PIC	10°	yes	full Ohm's

Realistic divergence greatly increases ignition energy; axial magnetic field 30-50 MG mitigates divergence



- Omega implosion experiments: compressed 50 kG seed field to:
30-40 MG (cylindrical¹), 20 MG (spherical²)
- Rad-hydro-MHD studies of B field compression have begun: H. D. Shay, M. Tabak

¹J. P. Knauer, Phys. Plasmas 17, 056318 (2010)

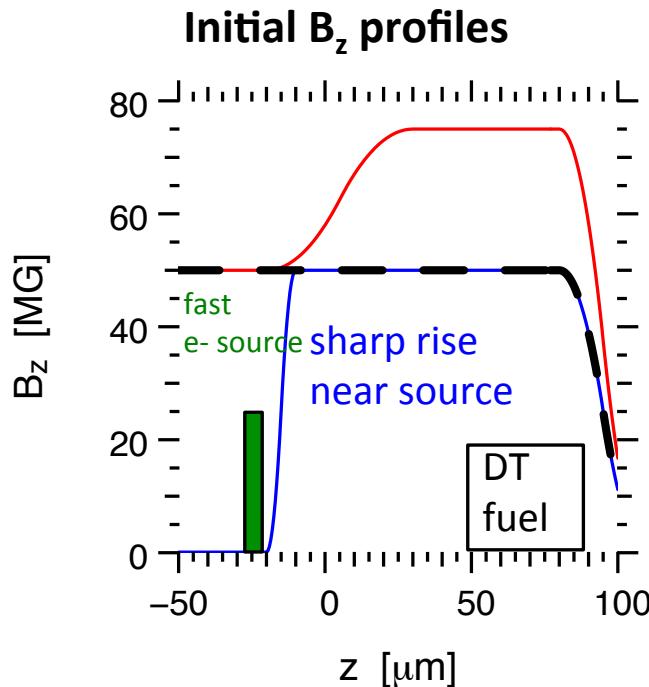
²P. Y. Chang et al., Phys. Rev. Lett 107(3):035006 (2011)

Axial magnetic field that increases in z leads to mirror force, reflects fast electrons

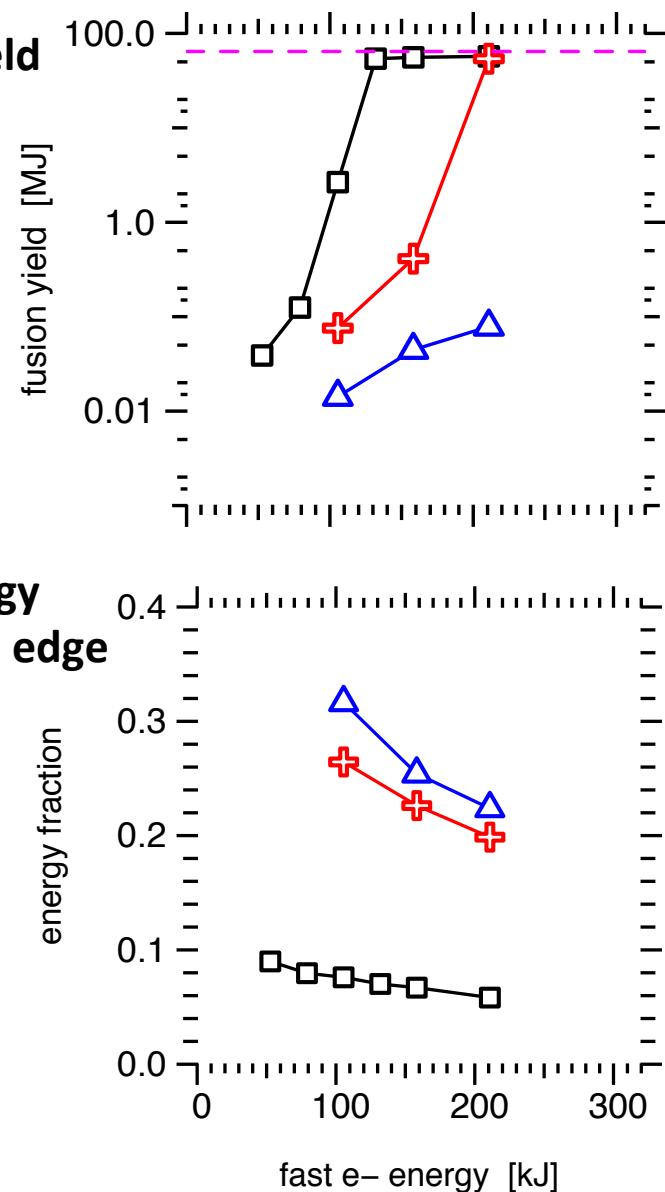
$$\nabla \cdot \vec{B} = 0 \rightarrow B_r = -\frac{1}{r} \int_0^r dr' r' \frac{\partial B_z}{\partial z}$$

$$\vec{F} = q\vec{v} \times \vec{B} \rightarrow F_z = -qv_\phi B_r$$

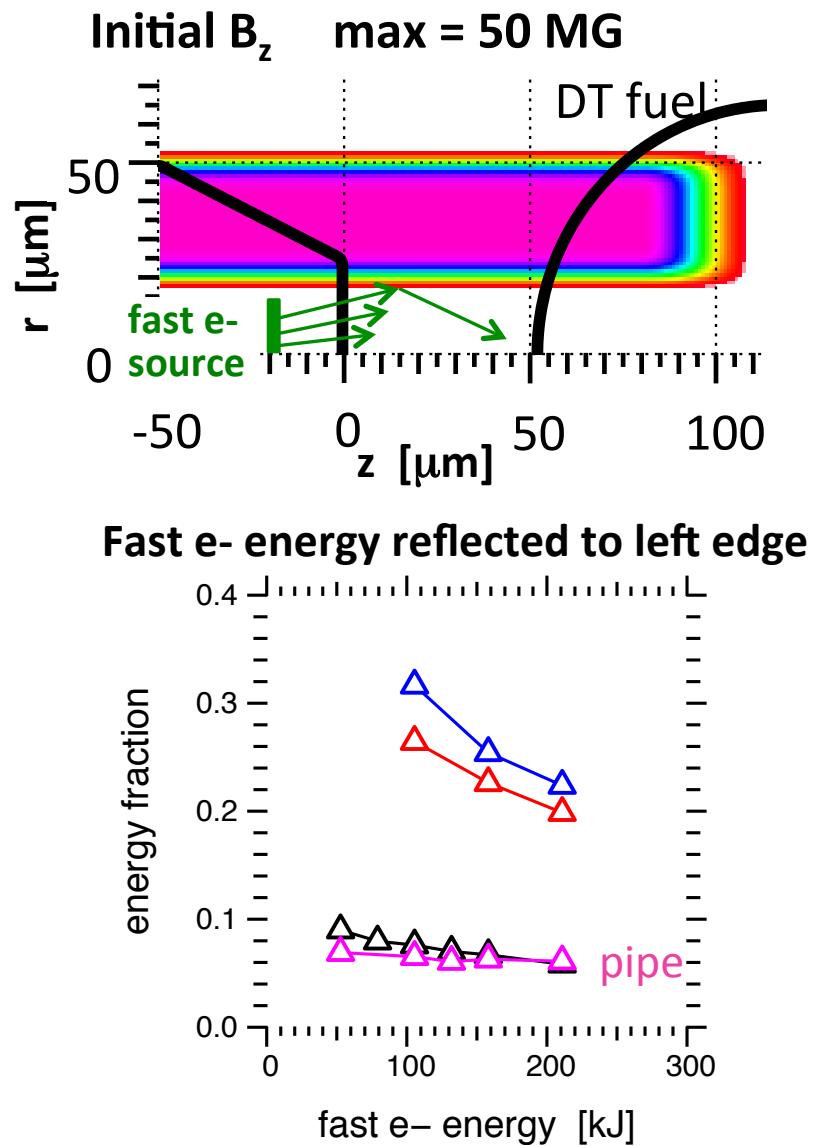
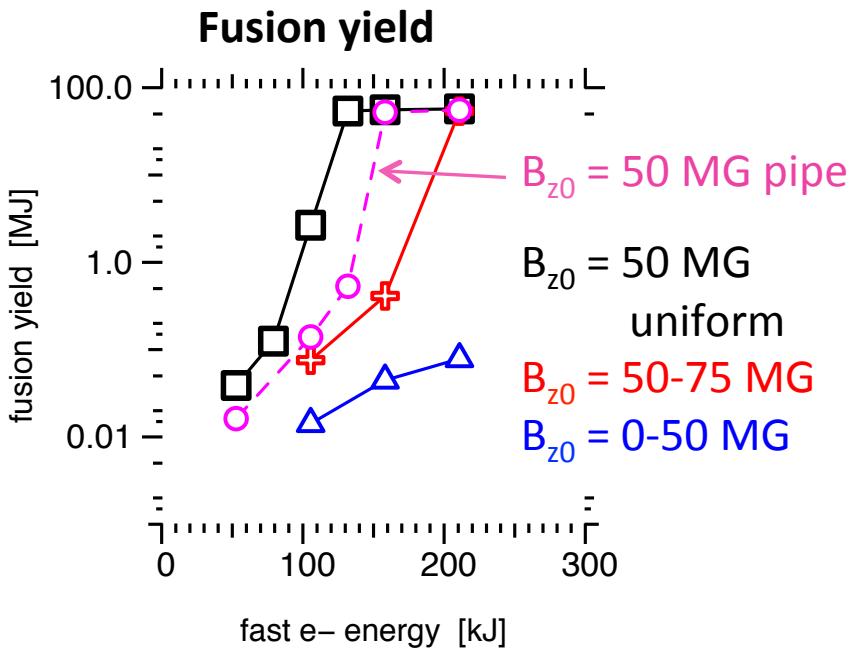
mirroring: F_z towards decreasing B_z



Fast e- energy reflected to left edge

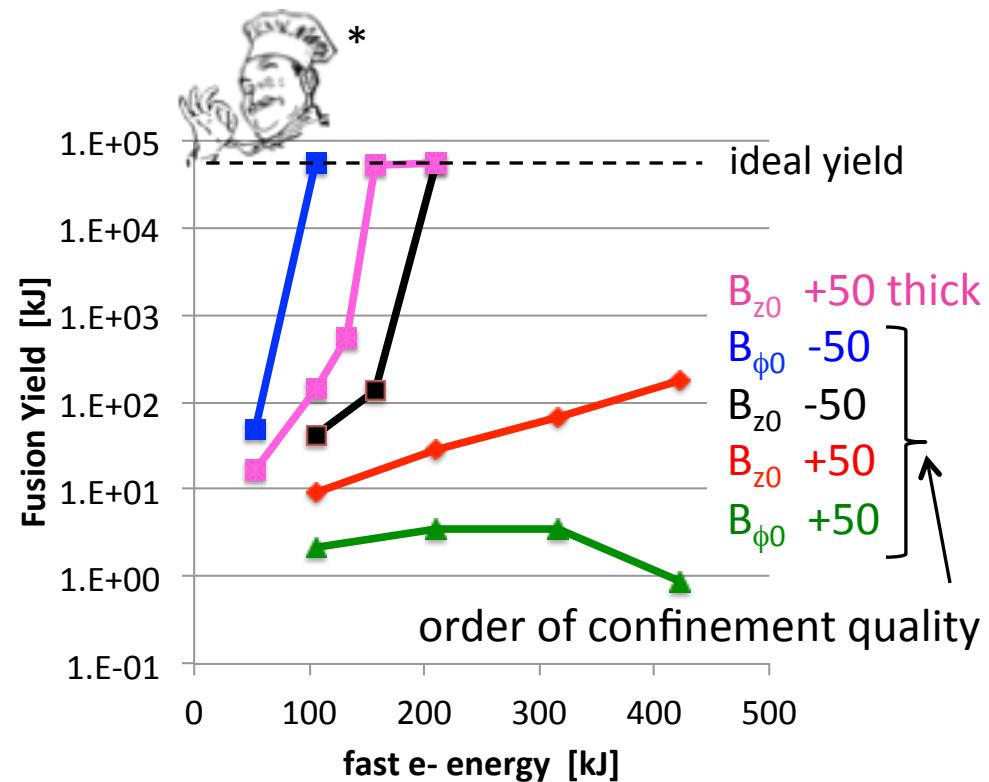
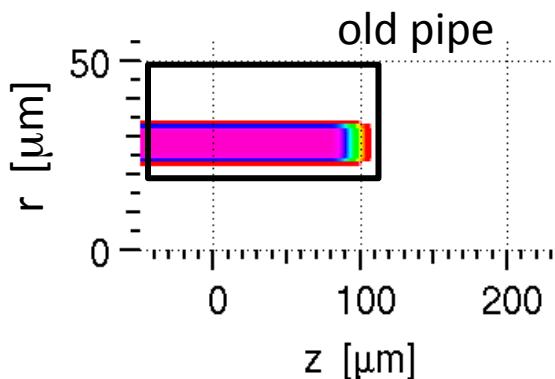


Magnetic pipe: hollow inside spot radius, avoids mirroring



Magnetic pipes: sign and direction (axial vs. azimuthal) matters

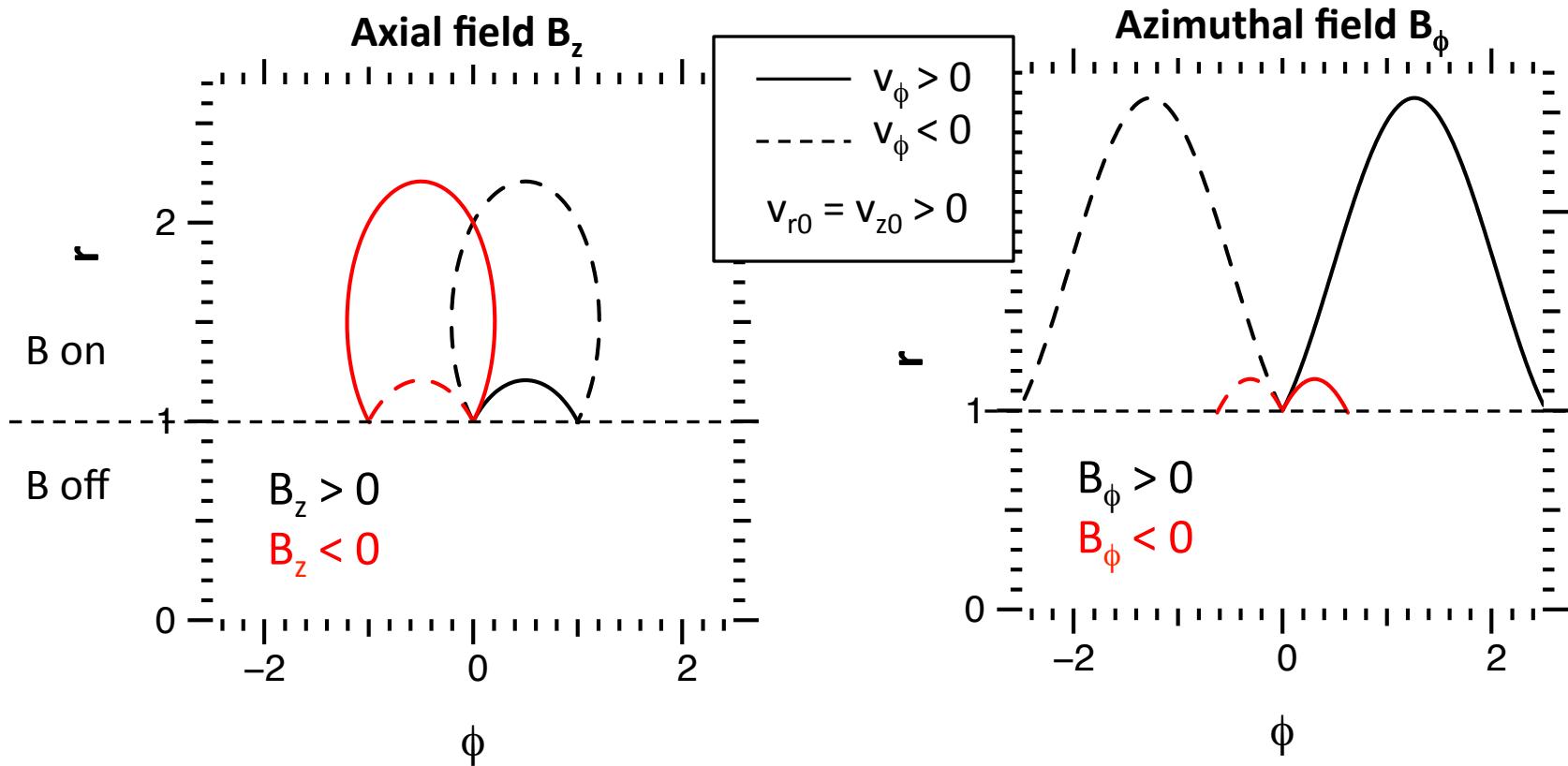
Thinner pipe: easier to assemble



- So far I've used $B_z > 0$, the wrong sign – sorry!
- Fast electrons self-generate azimuthal field in radial resistivity gradient:
Robinson and Sherlock, Phys. Plasmas 2007

* Courtesy C. Bellei

Orbits of electrons in magnetic pipe fields



Orbit-based quality of pipe confinement:

$$B_\phi < 0$$

$B_z < 0$ and $B_z > 0$ same

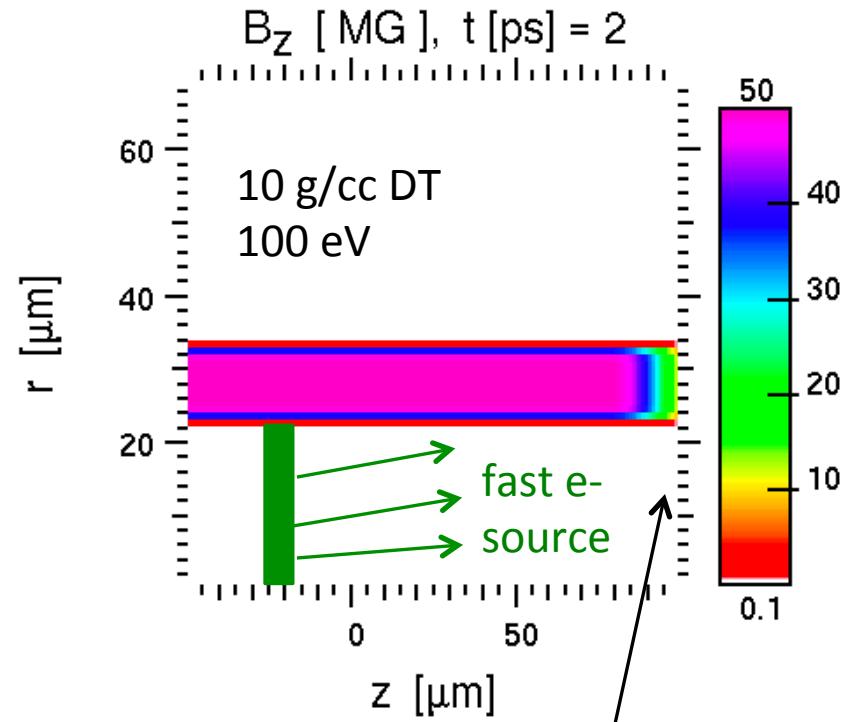
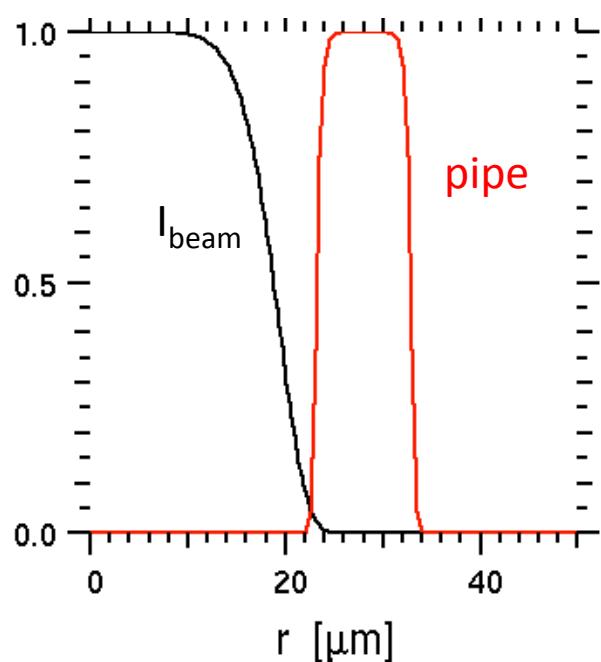
$$B_\phi > 0$$

Orbits explain performance of B_ϕ signs, and B_ϕ vs B_z – but not role of sign(B_z)

Cartesian geometry: $(r, \phi, z) = (x, y, z)$

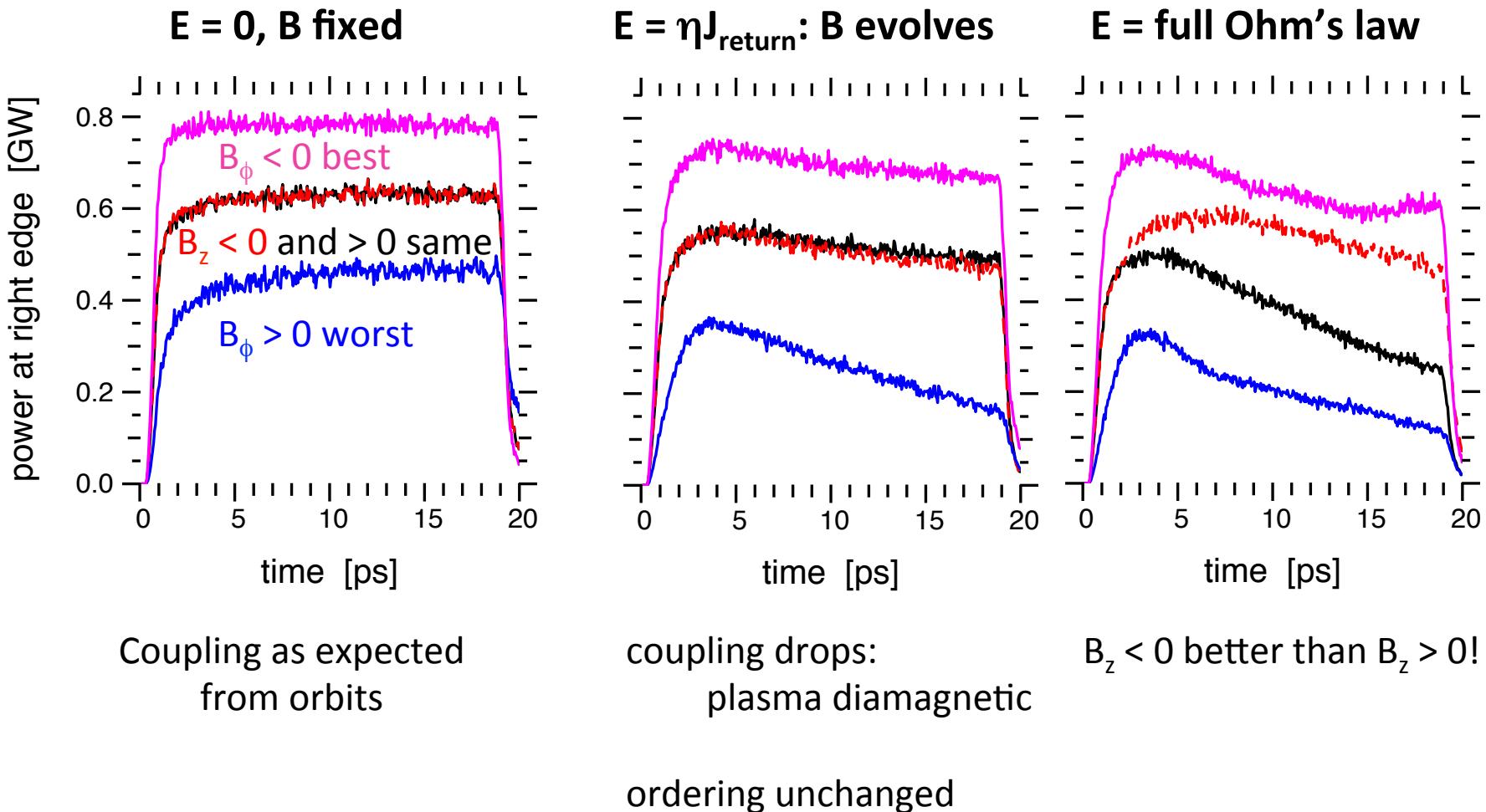
Magnetic pipes in simplified, uniform plasma

Zuma runs, no Hydra, no cone or dense fuel

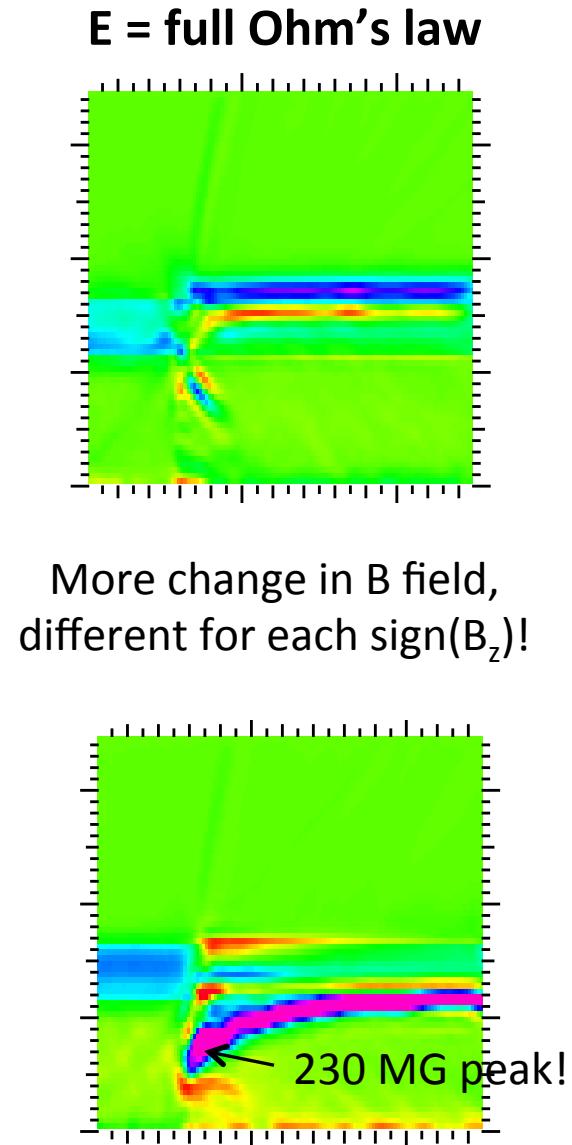
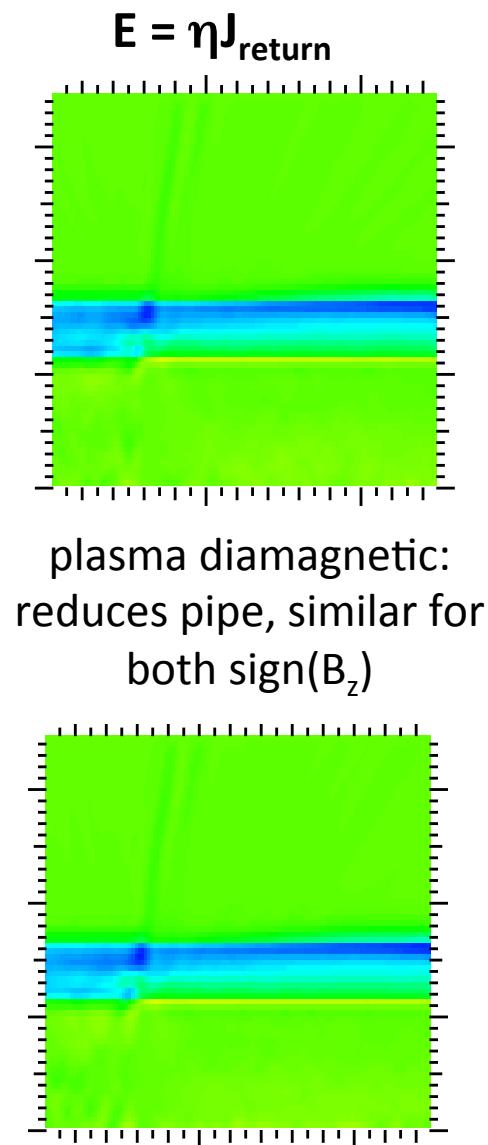
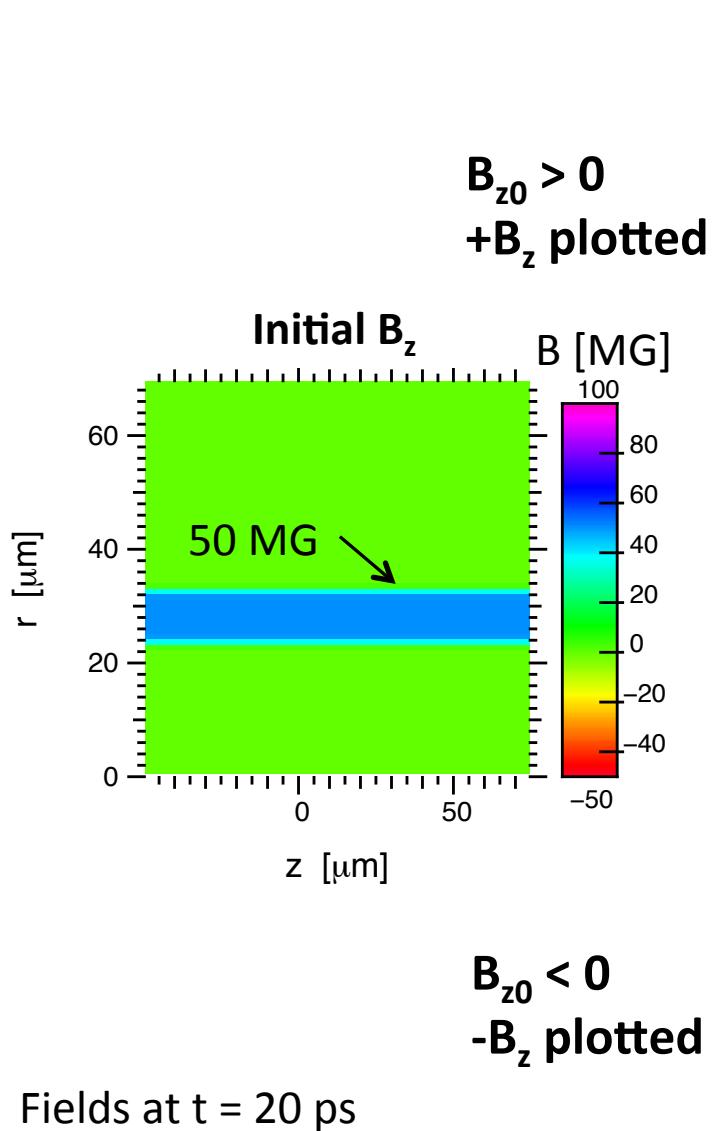


Next page: Power = rate energy exits at right, $r < 20 \mu\text{m}$, at most 1.3 MeV per electron (\sim stopping in hot spot)

Full Ohm's law gives different confinement based on sign(B_z):



Full Ohm's law: magnetic fields evolve differently than with $E = \eta J_{\text{return}}$, and for each sign (B_z)



Is fast ignition a pipe dream?

- Imposed, axial magnetic fields 30-50 MG recover ignition energy of artificially-collimated electron source
- Magnetic mirroring in increasing field reduces benefit
- Mirroring overcome with magnetic pipes – hollow out to e- source radius
- Pipe confinement best for one sign of B_ϕ – beats either B_z sign
 - Orbits explain this
 - Fast e- can self-generate in radial resistivity gradient
- $B_z < 0$ pipe confines better than $B_z > 0$
 - Orbits don't explain this!
 - Nor does resistive Ohm's law $E = \eta J_{\text{return}}$
 - Full Ohm's law does: B fields evolve differently